SOHO (Solar and Heliospheric Observatory)

The Solar and Heliospheric Observatory (SOHO) is a project of international cooperation between ESA (the EUROPEAN SPACE AGENCY) and NASA to study the Sun, from its deep core to the outer corona, and the solar wind. SOHO was launched on 2 December 1995, on top of an Atlas/Centaur combination, from Cape Canaveral Air-Force Base in Florida. It reached its operating orbit around the L1 Sun–Earth Lagrangian point in mid-February 1996. For more than two years this unique vantage position has allowed nearly uninterrupted observations of the Sun, 24 hours a day, 365 days a year.

The main scientific objectives of the SOHO mission are

- to study the SOLAR INTERIOR, using the techniques of HELIOSEISMOLOGY,
- to study the heating mechanisms of the solar CORONA through data obtained by imaging telescopes and spectrometers, and
- to investigate the SOLAR WIND and its acceleration processes, again by remote sensing, and by *in situ* particle measurements.

To achieve these objectives SOHO carries onboard a complement of 12 state-of-the-art instruments, developed and furnished by 12 international Principal Investigator (PI) consortia involving 39 institutes from 15 countries. Nine of these consortia are led by European PIs, and the three others by US PIs.

During the nominal mission, from 1 May 1996 to 30 April 1998, the SOHO spacecraft operated extremely well, exceeding its specifications in many instances, while the SOHO instruments collected a large number of data, allowing SOHO scientists to make substantial progress in all three science objectives. Scientific highlights from the nominal mission will be presented below. Because of SOHO's scientific success, ESA and NASA have both committed themselves to a mission extension of several years. On 24 June 1998, during routine maintenance operations, ground controllers lost contact with the spacecraft. Efforts to re-establish nominal communication succeeded seven anguish-filled weeks later, and a team of engineers from ESA and Matra-Marconi, the spacecraft contractor, succeeded in returning the spacecraft to full nominal status. All experiments onboard have been restored to the same operational status as before the accident, despite the extremes in heat and cold endured. In the aftermath of these events the third and last gyroscope onboard the spacecraft failed, but after some initial difficulties ground controllers succeeded in operating SOHO in a gyro-less mode, with the function of the gyros taken over by the reaction wheels.

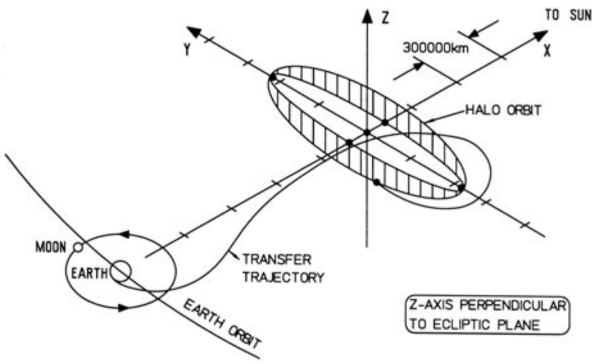

Figure 1. The SOHO orbit around the first Lagrangian point, 1.6 million km sunward from the Earth.

Development and launch

SOHO was first proposed in November 1982, in response to a call for mission proposals by ESA, as a high-resolution spectroscopic investigation of the upper solar atmosphere. In 1983 helioseismology was included as one of the science objectives. After a joint study by European and US scientists, the Science Program Committee of ESA approved SOHO as part of the Solar Terrestrial Science Program (STSP), to be implemented in collaboration with NASA.

ESA and NASA agreed that ESA would take the responsibility for developing the spacecraft, and NASA for the SOHO launch and operations. The 12 SOHO experiments were selected in 1988 after a combined ESA–NASA announcement of opportunity. The SOHO spacecraft was build by a consortium of European industries, led by Matra-Marconi.

SOHO is large, $4.3 \times 2.7 \times 3.7$ m^3, and weighs 1861 kg, with 655 kg for the payload and 250 kg of propellants. The maximum power supply from the solar cells is 1400 W, with a maximum payload consumption of 625 W. SOHO's reaction wheels are designed to provide short-term pointing stability better than 1 arcsec over 15 min, while the roll angle around the Sun is stabilized with the use of a star sensor unit to under 1.5 arcmin over 15 min. Two Gbits of solid state memory, backed up by a one Gbit tape recorder, can store the continuous scientific data rate of 40 kbit s^{-1}, plus 1.3 kbit s^{-1}, for more than 13 h. During continuous contact with the stations of NASA's Deep Space Network (DSN), another 160 kbit s^{-1} of MDI high-rate data are downlinked.

SOHO was launched on top of a Centaur-Atlas combination on 2 December 1995 at 8:08 UT. After one orbit around the Earth the Centaur engine was reignited to set SOHO on course towards the first Lagrangian point, about 1 million miles sunward from the Earth. The launch was so accurate, and the orbital maneuvers so efficient, that SOHO reached its halo orbit six weeks ahead of schedule, on 14 February 1996, with sufficient fuel left to maintain the (unstable) halo orbit for more than a decade, at least twice the time foreseen prior to launch.

The first four months of SOHO operations were devoted to commissioning and performance verification of the spacecraft and the scientific instruments. By the end of this period the spacecraft was shown to be in excellent shape, with a pointing accuracy of 3 arcmin, better by a factor of 2 than the specification, and a short-term (15 min) stability of 0.3 arcsec, exceeding the specification by a factor of 3. With some minor exceptions, the experiments were all found to operate nominally or better than anticipated.

Experiments and science investigations

An overview of the twelve science experiments onboard SOHO is presented in table 1. The experiments are grouped according to their science objectives. The three interior and surface experiments (GOLF, VIRGO and MDI) use the techniques of helioseismology to measure the properties of the solar interior. GOLF measures the net velocity fluctuations of the entire Sun, VIRGO the intensity variations of the Sun in a dozen zones, and MDI makes maps of the entire surface in velocity, intensity and magnetic field on a 1024 × 1024 CCD. The GOLF and VIRGO instruments are designed to achieve high absolute precision in order to detect the Sun's internal gravity waves (g-modes). MDI is geared towards higher order acoustic modes (p-modes), in order to probe the detailed structure of the SOLAR INTERIOR CONVECTION ZONE. MDI surface maps also allow us to follow the generation and evolution of magnetic fields on a GRANULATION to global scale, with a spatial and temporal resolution sufficient to follow the life-cycle of individual magnetic structures. The continuity of SOHO observations is essential for achieving SOHO's helioseismology objectives. To obtain a signal-to-noise ratio necessary to detect the low-amplitude g-modes, and to measure the frequency of the p-modes with the desired accuracy of a few tens of nanohertz, years of virtually uninterrupted data are required.

SOHO's remote sensing experiments study the outer atmosphere and solar wind. Three of those, SUMER, CDS and EIT, concentrate on the transition region and corona at moderate to high spatial and spectral resolution. The others, UVCS, LASCO and SWAN, avoid the disk to provide data on the outer corona, including the SOLAR WIND ACCELERATION region. The CELIAS solar extreme-ultraviolet monitor (SEM) is a very stable photodiode spectrometer that measures the full disk solar flux in He II at 304 Å, as well as the absolute integral flux between 170 and 700 Å.

SUMER is a UV telescope with a normal incidence spectrometer with high spatial and temporal resolution ($\sim$10 s). It measures line profiles and intensities of UV lines in the range from 500 to 1600 Å, with a resolution of 18 800 to 40 000. Thus SUMER can measure velocities down to 1 km s^{-1}. CDS operates at shorter wavelengths (150 to 800 Å), and consists of a Walter II telescope equipped with both a normal and a grazing incidence spectrometer. It determines line intensities in selected EUV lines to study the temperature and density of coronal structures. EIT obtains full-Sun high-resolution images, limited only by the 2.6 arcsec pixel size, in four emission lines, and corresponding to temperatures of 80 000, 1.3, 1.6 and 2.0 $\times 10^6$ K. EIT's observations provide the morphological context for the spectrographic data from CDS and SUMER.

LASCO is a triple coronagraph with nested concentric, and increasing annular fields of view. It also has a Fabry–Pérot interferometer for spectroscopic measurements with a spectral resolution of about 700 mÅ, in Fe XIV and X, Ca XV, Na D_2 and Hα. UVCS is an occulted telescope equipped with high-resolution spectrometers for spectroscopic observations of the solar corona out to 10 solar radii to determine the source regions, the acceleration and the heating of the solar wind. One UVCS grating is optimized for line profile measurements of Lyα, another for line measurements in the range from 944 to 1070 Å. SWAN, finally, maps the intensity of interplanetary Lyα, with two identical periscope systems, each of which observes one hemisphere at a resolution of 1 arcmin. Its goal is to determine the latitude distribution of the solar wind flux, and its variation. In addition it can measure the shape of the Lyα line at a resolution of about 3×10^5.

Of the three *in situ* particle experiments onboard SOHO, CELIAS studies the solar wind at L1, pristine in comparison with the data affected by the Earth's foreshock, which are collected by near-Earth spacecraft. The CELIAS proton monitor measures ions in the range 0.3 to 6 keV/e, and generates values of the solar wind proton bulk speed, density and north/south flow direction with a 30 s temporal resolution. The CELIAS mass determining time-of-flight (MTOF) sensor is a high-resolution mass spectrometer, which measures the solar wind's elemental and isotopic composition. CELIAS/CTOF, the charge determining time-of-flight sensor has obtained high time resolution charge state spectra for solar wind iron ions, but is no longer fully operational. Finally, CELIAS' suprathermal time-of-flight sensor (STOF) measures ionic charge states of particles with suprathermal energies from just above the solar wind up to low-energy solar flare particles (20–4000 keV amu^{-1}; see SOLAR FLARE OBSERVATIONS), thus bridging the gap between the solar wind instruments and the high-energy particle instruments ERNE and COSTEP.

ERNE and COSTEP are designed to detect Earthward traveling energetic particles ejected from the Sun in the course of flares and coronal mass ejections (CMEs; see SOLAR CORONAL MASS EJECTION: OBSERVATIONS). Electrons are recorded at energies from 44 keV to 50 MeV, and protons from 44 keV to over 100 MeV. Alpha particles are observed from a few MeV/nucleon to over 100 MeV/nucleon. Heavier elements, up to iron, can be identified up to 500 MeV/nucleon.

Operations and data archive

In nominal science operations each SOHO experiment carries out an individual synoptic or baseline science program, complemented for the remote sensing experiments and MDI by a coordinated mode, involving frequent joint

Table 1. An overview of the twelve science experiments on SOHO.

Experiment	Investigation	Technique	Bit rate (kb s^{-1})
Helioseismology			
GOLF (Global Oscillations at Low Frequency)	Global Sun velocity and magnetic field oscillations, harmonic degree $l = 0$–4	Na vapor resonant scattering cell, Doppler shift and circular polarization	0.160
VIRGO (Variability of Solar Irradiance and Gravity Oscillations)	Low degree ($l = 0$–7) irradiance oscillations and solar constant	Global Sun and low-resolution (12 pixels) photometers, active cavity radiometers	0.1
SOI/MDI (Solar Oscillations Investigation/ Michelson Doppler Imager)	Velocity oscillations with harmonic degree up to 4500	Doppler shift with Fourier tachometer, 4 and 1.5″ resolution	5 and 160
Solar atmosphere remote sensing			
SUMER (Solar Ultraviolet Measurements of Emitted Radiation)	Plasma flow characteristics (temperature, density, velocity) chromosphere through corona	Normal incidence spectrometer, 50–160 nm, spectral resolution 20 000–40 000, angular res. 1.2–1.5″	10.7 or 21
CDS (Coronal Diagnostic Spectrometer)	Temperatures and density: transition region and corona	Normal and grazing incidence spectrometers, 17–80 nm, spectr. res. 1000–10 000, angular res. 2″	11.5 or 23
EIT (Extreme-Ultraviolet Imaging Telescope)	Evolution of chromospheric and coronal structures	Full disk images (42′ × 42′ with 1024 × 1024 pixels) in He I, Fe IX, Fe XII and Fe XV	2.0 or 6.6 or 27
UVCS (Ultraviolet Coronagraph Spectrometer)	Electron and ion temperature densities, velocities in corona (1.3–10$R_\odot$)	Profiles and/or intensity of spectral EUV lines (Lyα, O VI, etc)	5
LASCO (Large Angle and Spectro-metric Coronagraph)	Coronal evolution, mass, momentum, and energy transport (1.1–30 $R_\odot$)	One internal and two externally occulted coronagraphs, Spectrometer for 1.1–3$R_\odot$	5.9 or 9.2 or 27
SWAN (Solar Wind Anisotropies Study)	Solar wind mass flux anisotropies and temporal variations	Scanning telescopes with hydrogen absorption cell for Lyα light	0.2
Solar wind 'in situ'			
CELIAS (Charge, Element, and Isotope Analysis System)	Energy distribution and mass, charge and charge state of ions 0.1–1000 keV/e	Electrostatic deflection, time-of-flight measurements, and solid state detectors	1.5
COSTEP (Comprehensive Suprathermal and Energetic Particle Analyser)	Energy spectrum of protons, α-particles, and electrons, composition of ions	Solid state detectors and electrostatic analysers	0.3
ERNE (Energetic and Relativistic Nuclei and Electron experiment)	Energy distribution and composition of ions (p, Ni), 1.4–540 MeV/n, and electrons 1–25 MeV	Solid state, and plastic and crystal scintillator detectors	0.71

operations programs (JOPs), occasional targets of opportunity, and regular campaigns with other spacecraft and ground-based observatories (GBOs).

The SOHO experiments were designed to complement each other, and through intense and innovative use of the Internet, SOHO has lifted the standard, frequency and documentation of coordinated solar observations to a new level. Images, observing sequences and target coordinates are exchanged instantaneously, while the data are automatically linked through the SOHO catalogs. Hundreds of campaigns have been carried out during the nominal mission. These vary from large-scale campaigns of several hours daily for one or two weeks, involving GBOs all over the world as well as other spacecraft (YOHKOH, TRACE, ULYSSES), to instrument intercalibrations of an hour or two, occasionally supported by rocket underflights.

The center of SOHO operations is the Experiment Operations Facility (EOF) at NASA's GODDARD SPACE FLIGHT CENTER, where experiment commanding, real-time coordination and long-term planning are executed. Representatives of the six interactive experiments (SUMER, CDS, EIT, MDI, UVCS and LASCO) are permanently present at the EOF to operate the mission in collaboration with the NASA Flight Operations Team and the ESA/NASA Project Scientist Team. The science observing programs are planned through a regular, nested series of meetings, that lead to a schedule that is both predictable enough to prevent overburdening operations scientists, and flexible enough to allow rapid reaction to observing opportunities.

SOHO is unique among solar physics missions in that data are received 'live', and the experiments commanded in near real time directly from the EOF for about 8 h a day. Scientists, from behind their workstations, can retarget and reprogram their experiments in a matter of minutes in response to events on the Sun.

Four SOHO data archives are being constructed, one in the US, at Goddard Space Flight Center, and three in Europe, at Medoc in Orsay, RUTHERFORD–APPLETON LABORATORY in the UK, and in Torino. These archives contain all experimental data, except for the MDI helioseismology data, which are stored in a separate facility at Stanford. To make the data easily accessible through the Internet for the widest possible group of scientific users, and to facilitate multi-experiment data analysis, the SOHO archive has a uniform data format (FITS), uniform access to all experimental data, a campaign catalog that cross-links experimental data of coordinated observations, a collection of synoptic data from observatories world wide, and a complete set of analysis software. The main SOHO catalog, an event catalog and the experiment catalogs round out the archive.

Science highlights

Exploitation of the enormous number of data from the SOHO nominal mission is only in its initial phase, but already a large number of exciting new results have been announced. A brief synopsis is given below.

Solar surface and interior

MDI medium angular degree data have provided the most precise measurements of the sound speed profile and the differential rotation profile within the Sun, thus setting new boundaries for the solar model

Application of a new technique, called time–distance helioseismology, to high-resolution MDI data has provided the first images of the convection zone of a star; maps of vertical and horizontal flow velocities, as well as sound speed variations in the convection zone, just below the visible surface.

MDI data have revealed a jet-like flow near the poles, which is totally inside the Sun and cannot be seen at the surface. Circling the Sun at about 75 deg latitude, this flow consists of a flattened oval region about 30 000 km across where material moves about 10% faster than its surroundings.

MDI data have also revealed at least six differentially rotating belts, three in each hemisphere. These belts are more than 65 000 km across and they move about 15 km h^{-1} faster than their surroundings.

The use of the new time–distance helioseismology technique in analysing MDI data has yielded that the entire outer layer of the Sun, to a depth of at least 25 000 km, is slowly but steadily flowing from the equator to the poles at about 80 km h^{-1}, fast enough to transport an object from the equator to the pole in just over a year.

High-precision MDI measurements of the Sun's shape and brightness obtained during two special 360° roll maneuvers of SOHO have produced the most precise determination of solar oblateness ever. There is no excess oblateness. These measurements unambiguously rule out the possibility of a rapidly rotating core and any significant solar cycle variation in the oblateness.

Results from the radiometers and photometers of VIRGO confirm that active regions modulate total and spectral irradiance on time scales of days to weeks.

Solar corona and solar wind

The UVCS coronagraph has revealed dramatic differences in the line widths of the strong hydrogen Lyα line and even more so in the resonance lines of O VI in coronal streamers and CORONAL HOLES at heliocentric heights from 1.25 out to 3.5 solar radii. Preferential acceleration of high mass ions affords one possible explanation for generating the observed velocities in the O VI ions.

Combined Doppler-dimming measurements of UVCS, LASCO white-light images of the solar corona, and radio scintillation measurements by the Galileo spacecraft have yielded new insight into the origins of the slow and fast solar wind. While the prevailing view is that the fast solar wind originates only in polar coronal holes and their equatorial extensions, the new measurements are interpreted as evidence that the slow solar wind is limited to the axes (or 'stalks') of coronal streamers while the fast solar wind dominates the corona.

A UVCS spectroscopic study of the composition in coronal streamers has revealed an ionization temperature of 1.6×10^6 K. The elemental abundances in the leg of the streamers and in ACTIVE REGION streamers are similar to those observed in the slow solar wind, indicating that the slow solar wind originates at the legs of the coronal streamers.

The CDS and SUMER spectrometers have observed extensive evidence of explosive events in transition-region lines. These could be the signature of MAGNETIC RECONNECTION events in nearby small magnetic dipoles, observed in MDI magnetograms. These events seem to account for a substantial part of the energy that is needed to heat the corona.

Coordinated measurements by SUMER and CDS have provided new observations of the temperature structure of coronal holes. The temperature measured at the base has a higher value than anticipated, of the same order as that of closed field regions (about 10^6 K), but it decreases much more rapidly with height than had been expected, falling to about 0.3×10^6 K at 1.3 solar radii. This is not consistent with a thermally driven fast solar wind.

Time-lapse sequences of white-light images from the LASCO coronagraph, obtained during sunspot minimum conditions in 1996, have been used to measure, for the first time, the acceleration of the solar wind. The outflow of about 150 features in the streamer belt has been tracked between 3 and 30 solar radii. The speed versus radial distance profiles cluster around a parabolic path characterized by a constant acceleration of about 4 m^{-2} throughout the field of view. That profile is consistent with an isothermal solar wind expansion at a temperature of $\approx 1.1 \times 10^6$ K and a sonic point around 5 solar radii.

EIT and LASCO have recorded the very onset and evolution of several Earth-directed CMEs, a few of which actually hit the Earth's magnetosphere (see MAGNETOSPHERE OF EARTH). This type of observation holds considerable promise for the further development of space weather forecasting methods. The LASCO instrument is collecting an extensive database for establishing firm statistics on CMEs and their geomagnetic effects.

The LASCO coronagraphs have discovered more than 50 sungrazing comets, several of which were observed crashing into the Sun (see COMETS: KREUTZ SUNGRAZING).

The *in situ* particle detectors (ERNE and COSTEP) regularly detect high-energy protons, electrons and alpha-particles, in the aftermath of prominence eruptions and CMEs, while CELIAS, SOHO's solar wind analyser, has doubled the number of elements and isotopes previously recorded in the solar wind. During a Venus disk passage CELIAS also observed, for the first time from such a large distance, pick-up ions from the Venusian ionosphere, finding a much smaller diffusion cone than anticipated.

SWAN, looking away from the Sun, has recorded full-sky Lyα maps at a resolution and signal-to-noise ratio of at least a factor 10 better than previous observations. From these maps, the latitude distribution of the solar wind is determined.

Bibliography

SOHO Web Site with the latest information on mission status and observing programs, and a picture and movie gallery: `http://sohowww.nascom.nasa.gov/index.html`

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